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-Technical Report-

Cummins 903 Low Viscosity Synthetic Oil Test

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April 17, 2012

U.S. Army Tank Automotive Research,
Development, and Engineering Center
Detroit Arsenal
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PREFACE

The U.S. Army's Tank Automotive Research and Development Center, Ground Vehicle Power & Mobility, utilizing test cell 5 in building 212, performed all testing. The test duration was from September to December 2011.

The purpose of the test was to assess the Cummins 903 performance and endurance during a 400-hour Modified NATO test.

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14. ABSTRACT

A 400 hour modified NATO endurance test was conducted to assess the performance and endurance of the Cummins 903 engine using the Single Common Powertrain Lubricant (SCPL) developed by TARDEC's Fuels and Lubricants Technology Team (FLTT). The FLTT group in building 210 provided the funding to purchase the Cummins 903 engine and supplied the SCPL that was used during testing. The test was run to look at the engines performance and endurance throughout the 400-hour test along with comparing the engine to previous engine data that was obtained at the same test conditions using standard 15W-40 engine oil. Test conditions are as follows, standard conditions for performance testing only: 77 deg F ambient air and 86 deg F fuel supply temperature, modified desert operating conditions for performance and 400 hour endurance testing: 120 deg F ambient air and 175 deg F fuel supply temperature. The Cummins 903 using SCPL passed the 400-hour modified NATO engine test conducted at desert-like operating conditions. The data showed the engine to perform well while operating with SCPL during the 400-hour endurance test under desert operating conditions, although anomalies in oil pressure and an oil leak after the 400-hour endurance test were noted. TARDEC's Fuels and Lubricant Research Facility at Southwest Research Institute has been commissioned to tear down the engine, conduct a complete analysis of the engines condition and provide a report on their findings.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

This final report documents the Engine Endurance Testing conducted by U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). The TARDEC Fuels and Lubes group of building 210 provided a Cummins VTA903-T600 BHP @ 2600 RPM for evaluation. The performance and endurance of the engine was tested using a low viscosity synthetic oil (i.e., Single Common Powertrain Lubricant), which is in consideration for military use because of its ability to perform in different operating conditions: arctic and desert temperatures.

In July 2011, the TARDEC Fuels and Lubes group contacted TARDEC Ground Vehicle Power and Mobility (GVPM) to schedule the engine testing. Negotiations between the TARDEC Fuels and Lubes group office and TARDEC GVPM resulted in approval to test the engine at the TARDEC test facility building 212. TARDEC provided a test plan and procedures to the Fuels and Lubes group for approval.

The Cummins 903 arrived at TARDEC August 2011. The engine was set up in test cell 5; building 212. Dynamometer testing was conducted in accordance with the Cummins 903 test plan (APPENDIX A). Full Load and Part Load performance tests were conducted along with the modified 400-hour NATO endurance test. Testing was completed on Wednesday March 7, 2012.

KEY FINDINGS

- The Cummins 903 using the Single Common Powertrain Lubricant (SCPL) showed insignificant power differences when compared to another Cummins 903 engine ran on military standard 15W-40 oil under the same conditions. This data can be viewed in the results section of this report.
- The Cummins 903 had unexplainable oil pressure and flow measurements during the 400-hour endurance test when operating with the SCPL. This data showed changes in pressure and flow during different portions of the 400-hour endurance test. This data can be viewed in the results section of this report.
- The Cummins 903 operated using the SCPL had similar blow-by as the Cummins 903 engine ran on 15W-40 oil. The similar blow-by numbers shows that the engine operated using SCPL did not suffer excessive piston ring wear allowing combustion gases to travel from the combustion chamber and into the crank case.
- The Cummins 903 operated using the SCPL passed the 400-hour endurance test.
- The Cummins 903 operated using the SCPL experienced a large amount of oil loss from the rear main during the 400-hour performance test. Further investigation are required to determine the cause..

1 OBJECTIVE

The objective of this effort was to perform a modified 400-hour NATO endurance test using JP-8 fuel and the SCPL in accordance with the Cummins 903 Test Plan (Appendix A) to assess any possible performance, durability, and reliability variances in comparison to 15W-40. Oil samples were retrieved from the engine at 50-hour intervals to be tested by TARDEC Fuels and Lubricants Technology Team (FLTT) to monitor the tribological state of the engine throughout the test. The data collected from the engine test and oil testing will be used to verify the performance of the oil. The modified 400-hour NATO test was run at desert operating conditions (DOC) of 120 deg F ambient air and 175 deg F fuel supply temperature. For comparison to a previous test run using 15W-40, an additional engine performance test was run at standard operating conditions of 77 deg F ambient air and 86deg F fuel supply temperature. All data collected from the engine test will be analyzed and compared to a recently run Cummins 903 engine test, which was run on military standard 15W-40 oil (currently used in the majority of all military ground vehicle engines), and JP-8 fuel.

2 INTRODUCTION

This Final Technical Report is submitted by the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC), which describes the performance evaluation and analysis of the testing results for the Cummins 903 engine on low viscosity synthetic oil. The testing was sponsored by the TARDEC Fuels and Lubricants team and performed by TARDEC GVPM.

The Cummins 903 engine was placed in TARDECs' building 212, test cell 5 in August 2011. The engines fuel, air, oil, coolant, exhaust, and crankshaft were instrumented with thermal couples, pressure transducers, flow meters, and a dynamometer in order to obtain the necessary data to study the engines behavior during the Modified NATO endurance test.

The test work was undertaken in support of studying the effects of low viscosity synthetic oil in a Cummins 903 engine over a 400-hour Modified NATO test. This program will show the performance effects of the low viscosity synthetic oil while operating in desert like conditions for 400 hours.

The U.S. Army TARDEC Fuels and Lubricants Technology Team (FLTT) are seeking to develop an all-season (arctic-to-desert), fuel efficient, multi-functional power train fluid with extended drain capabilities. This program, known as the Single Common Power train Lubricant (SCPL) program, will leverage state-of-the-art base oil and additive technologies to significantly improve upon current military lubricants and act as an enabler for future power train technologies. The first phase of this program demonstrated the technical and economic feasibility of the SCPL concept. In the second and current phase, lessons learned from the technical feasibility will be used to guide the development of candidate SCPLs. Candidate SCPLs will be evaluated in military engines under desert operating conditions in a laboratory environment. The third and final phase will demonstrate SCPLs candidates in an operational environment during field-testing throughout the CONUS.

Table 1: Engine Information

General Engine Data

Type	**4 Cycle: 90^0 VEE; 8 Cylinder**
Aspiration	**Turbocharged & Aftercooled**
Bore & Stroke - in. (mm)	**5.5(140) X 4.75 (121)**
Displacement -in^3 (liter)	**903 (14.8)**
Compression Ratio	**15.5 : 1**
Dry Weight -lb (kg)	**2650 (1200)**
Wet Weight - lb (kg)	**2780 (1260)**
Moment of Inertia of Rotating Components (Excluding Flywheel) - lb-ft^2 ($kg{*}m^2$) -	**16.3 (0.68)**
Firing Order	**1-5-4-8-6-3-7-2**
Maximum bending moment at rear face of block - lb.-ft. (N*m)	**1000 (1350)**

Air Induction System

Maximum Inlet Restriction with Clean Filter - in. H_2O (kPa)	**15.0 (3.7)**
Maximum Inlet Restriction with Dirty Filter - in. H_2O (kPa)	**25.0 (6.3)**
Maximum Operating Ambient Air Temperature - ^0F (^0C)	**125 (52)**

Exhaust System

Maximum Back Pressure imposed by Piping and Silencer - in. Hg (kPa)	3 (15)
Exhaust Pipe size normally acceptable - in. (mm)	6.0 (152)
Maximum Bending Moment to the Turbocharger Exhaust Outlet Flanges - Lb*ft (N*m)	30 (41)

Lubrication System

Oil Pressure @ idle - (Minimum) - PSI (kPa)	10 (69)
Oil Pressure @ 2900 RPM - (Range) - PSI (kPa)	40 - 60 (276 - 414)
Total Pump Oil Flow @ 2600 RPM (Nominal) - U.S. GPM (liter/min)	40 (152)
Oil Capacity of Pan - U.S. Gal. (liter)	- 7.0 (26.5)
Total Oil System Capacity - U.S. Gal. (liter)	9 (34)
Maximum Allowable Oil Temperature - ^{0}F (^{0}C)	280 (138)
Angularity of Standard Oil Pan -Front Down	45 ^{0}
Angularity of Standard Oil Pan -Front Up	45 ^{0}
Angularity of Standard Oil Pan -Right Side Down	45 ^{0}
Angularity of Standard Oil Pan -Left Side Down	45 ^{0}

Cooling System

-

Coolant Capacity - Engine Only - U.S. Quart (liter)	36 (34)
Standard Modulating Thermostat - (Range) - ^{0}F (^{0}C)	180-200 (82-93)
Minimum Radiator Cap Pressure - PSI (kPa)	15 (103)
Maximum Coolant Temperature (Engine Out) - ^{0}F (^{0}C)	230 (110)
Minimum Recommended Coolant Temperature - ^{0}F (^{0}C)	160 (71)
Minimum Fill Rate - U.S. GPM (liter/min)	5 (19)
Minimum Coolant Expansion Space - % of System Capacity	5
Minimum Drawdown - U.S. Quart (liter)	13 (12)
Maximum Deaeration Time - Minutes	25

Fuel System

Maximum Fuel Consumption at Maximum Rated Output and Speed - lb/hr (kg/h)	207 (94)
Maximum Fuel Flow to Pump at Maximum Rated Output and Speed - lb/hr (kg/h)	1000 (454)
Maximum Restriction @ PT Pump Inlet - With Clean Filter - in Hg (mm Hg)	4.0 (100)
Maximum Injector Return Line Restriction - With Check Valves - in Hg (mm Hg)	6.5(165)
Maximum Injector Return Line Restriction - Without Check Valves - in Hg (mm Hg)	2.5 (64)
Minimum Fuel Tank Vent Capability - ft^3/hr (liter/h) [with 2.5 in Hg (63 mm Hg) or less Back Pressure	15 (425)
Primary Fuel	DF2
Alternate Fuels	DF1, DFA, JP8, JP5, JET-A, JET-A1

Starting and Electrical System

Minimum Recommended Battery Capacity - Cold Soak at 0^0F (-18^0C) or Above	
Engine Only (De-Clutched Load) - Cold Cranking Amperes - with 24 Volt Starter - CCA	900
Engine Only (De-Clutched Load) - Reserve Capacity - with 24 Volt Starter - Minutes	320
Maximum Resistance of Starting Circuit - with 24 Volt Starter - Ohms	0.002
Minimum Ambient Temperature For Cold Start Using On-Engine Systems- ^{0}F (^{0}C)	-25 (-31.67)
Minimum Cranking Speed Required For Unaided Cold Start - RPM	120

General Performance Data

Minimum Low Idle Speed - RPM	800 +/- 25
Minimum No Load Governed Speed	2900
Maximum No Load Governed Speed	3073
Maximum Over speed Capability (15 Second Maximum) RPM	3300
Crankshaft Thrust Bearing Load Limit - Maximum Intermittent - lb (N)	2500 (11,000)
Crankshaft Thrust Bearing Load Limit - Maximum Continuous - lb (N)	1250 (5,500)
Maximum Power from Front Power Take-Off in a Straight Torque Drive - HP (kW)	600 (448)

Maximum Rating Performance Data	**Advertised Power**	**Peak Torque**
Gross Power Output - BHP (kW)	600 (448)	460 (343)
Engine Speed - RPM	2600	2000
Torque - lb.-ft. (N*m)	1212 (1643)	1225 (1661)
Nominal Rail Pressure - PSI (kPa)	136 (937)	91 (627)
Intake Manifold Pressure - in Hg (mm Hg)	45 (1125)	30 (750)
Break Mean Effective Pressure - PSI (kPa)	202 (1393)	202 (1393)
Piston Speed - ft/min (m/sec)	2060 (10.5)	1585 (8)
Friction Horsepower - HP (kW)	83 (62)	48 (36)
Inlet Air Flow - CFM (liter/sec)	1440 (680)	870 (411)
Exhaust Gas Flow - CFM (liter/sec)	3270 (1543)	2335 (1102)
Exhaust Gas Temperature - ^{0}F (^{0}C)	930 (497)	1040 (553)
Heat Rejection to Ambient - BTU/min (kW)	2553 (44.8)	1890 (33)
Heat Rejection to Coolant - BTU/min (kW)	14,700 (258)	10,850 (190)
Maximum Radiator Coolant Flow - U.S. GPM (liter/min)	150 (568)	115 (435)

Table 2: SCPL Chemical/Physical Guidelines

Property	**Minimum Acceptable**	**Target**
KV@-40C, cSt., max.	16,000	12,000
KV@-48C, cSt., max.	55,000	45,000
Pour Pt, °C, min.	-55	-60
LT Cranking @ -35C, cP, max.	4700	4400
LT Pumping @ -40C, cP, max.	14,000	12,000
Brookfield @ -40C, cP, max.	13,000	10,000
Volatility, NOACK, %, max	11	10
Shear Loss, CEC L-45-T-93 (KRL), % loss, max.	8	6

3 TEST PROCEDURE AND EQUIPMENT

The 400 hour modified NATO test was conducted within the engine manufacture’s maximum allowable limits Engine oil sump temperature of 280 deg F and coolant out of engine temperature of 230 deg F.

An overall view of the Cummins VTA903 engine test setup mounted to the absorption dynamometer is shown in Figure 1.

Figure 1: Cummins VTA903-T600, Bldg. 212, Cell 5

The instrumented Cummins 903, serial number 95523 and engine number 37236156, and all supporting controls, data acquisition equipment, dynamometer, and associated instrumentation were assembled in test cell 5. Test cell 5 is located in building 212 at U.S. Army TARDEC in Warren MI. Power was absorbed from the Cummins engine with one eddy current dynamometer Figure 2, from the Midwest Dynamometer and Engineering Company model number 2025A and absorbs 700 HP from 1000 to 4000 RPM. Torque was measured using a load arm length of 21inches (+/- .001 inches) and a 3000 lb (+/- .4%) BLH Electronics load cell (SN K571554). The dynamometer curve is located in Appendix E, Figure E1. The engine was mated to the dynamometer from the output flange of the Cummins VTA903 crankshaft by a 23.45 inch (fully extended) drive shaft, Ringfeder Corp. model 43-51.3020 and a flywheel coupling, Ringfeder

Corp. model number 43-91.8140 which were dynamically balanced at 2600 RPM and have a maximum torque of 22,129 ft-lb.

The engine’s crankshaft, induction air, fuel, coolant, oil, and exhaust circuits were instrumented with thermal couples, flow meters, pressure transducers, and magnetic speed sensors. These pieces of instrumentation were used to monitor the vehicles components while on test. The thermocouples used were J and K types. J type thermocouples (WATLOW, +/- 2^{o} C), were used to monitor air induction, engine coolant, and engine oil temperatures. The K type thermocouples, (WATLOW +/- 2^{o} C), were used in monitoring the engines exhaust system. The water tower flow (Flow Tech model FT-32AEU2-LEG-1, +/-0.123% of full operating range), Figure 3, engine oil flow (Flow Tech model FT-16AEU4-LEG-1, +/-0.123% of full operating range), Figure 4, and the induction air flow (Vortex Serial Number 95221443), Figure 5, were measured using turbine and vortex shedder type flow meters which were specifically calibrated for 15W40 oil, water, and air. These flow measurements were essential in monitoring the cooling systems` heat rejection. A J-TEC blow by meter (serial number 10007, +/- 2% FS), Figure 6, was also attached to the engines breathers that sit atop of the engines valve covers. The blow by meter was used to monitor the rate of combustion gases flowing past the piston rings. The engine was also outfitted with static pressure taps for pressure transducers, Figure 8, on the oil, air, and coolant circuits. The pressure measurements were used to monitor restriction levels in particular circuits with respect to the manufacturer’s and NATO’s maximum allowable pressure restriction limits for the engines application. A FUTEK fuel scale (serial number 263167, mass measurement variance +/-0.0125 and time measurement variance of +/-0.05 sec) and signal conditioner (serial number 325206), Figure 7, were used to monitor the engines fuel consumption during the test. A replacement FUTEK fuel scale (serial number 263170 mass measurement variance +/-0.0125 and time measurement variance of +/-0.05 sec) and signal conditioner (serial number 279342) were implemented because of unreliable fuel consumption measurements from the original fuel monitoring system. Table 3 shows the instrumentation list that includes the items mentioned above.

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Figure 2: Testing Components, Dynamometer and Driveline

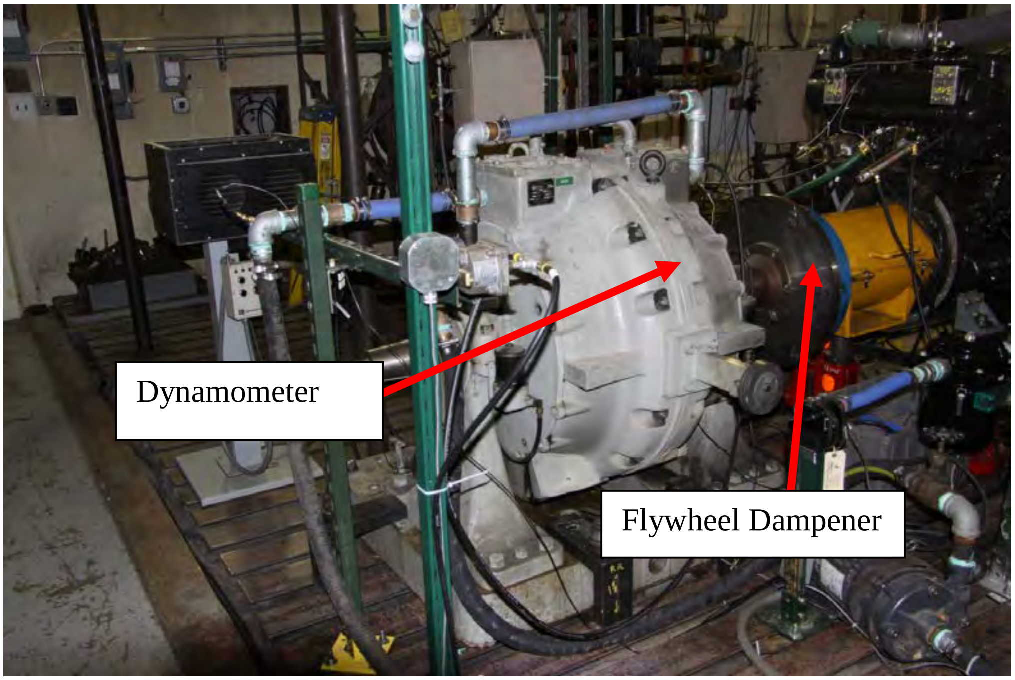

Figure 3: Testing Components, Water Tower Flow Meter

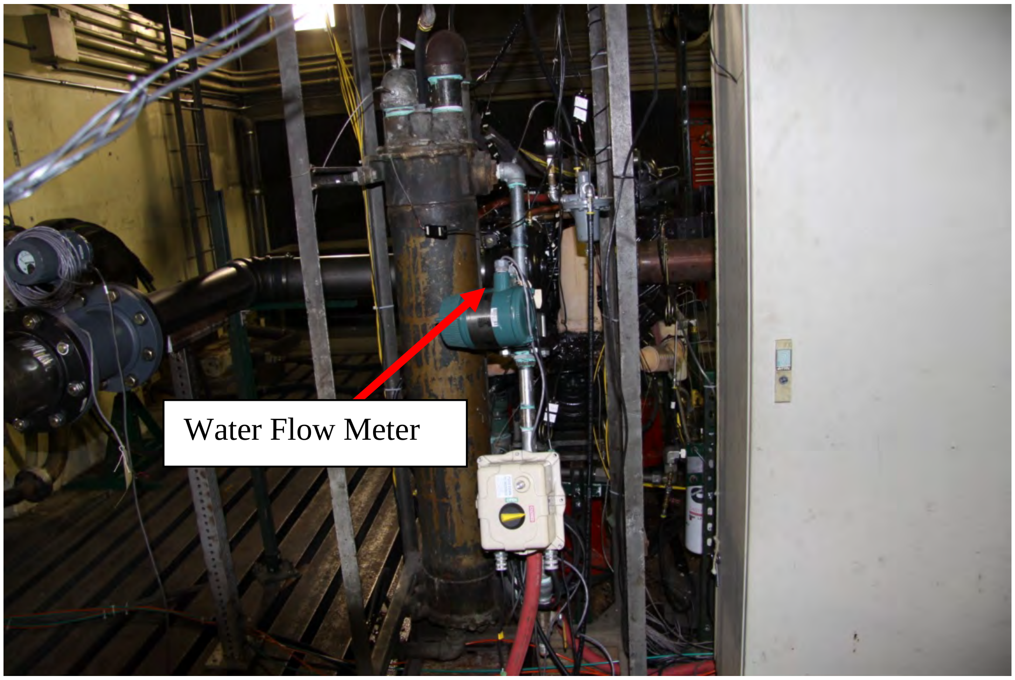

Figure 4: Testing Components, Engine Oil Flow Meter

Figure 5: Testing Components, Induction Air Flow Meter

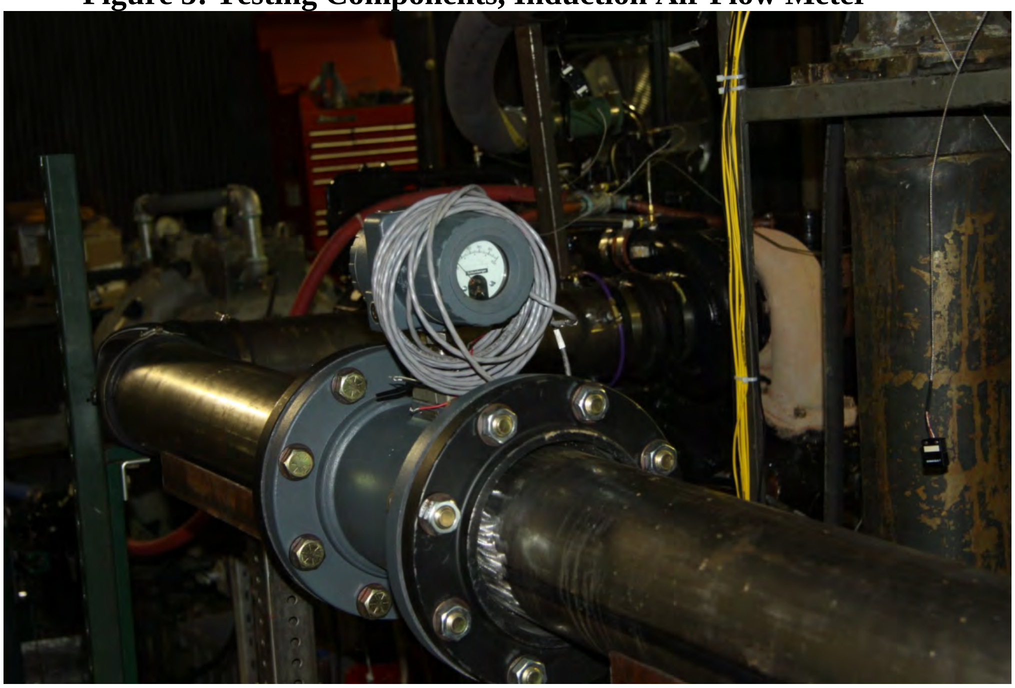

Figure 6: Testing Components, Pump and Blow-by Meter

Figure 7: Testing Components, Fuel Scale and Signal Conditioner

Figure 8: Testing Components, Pressure Transducer Cabinet

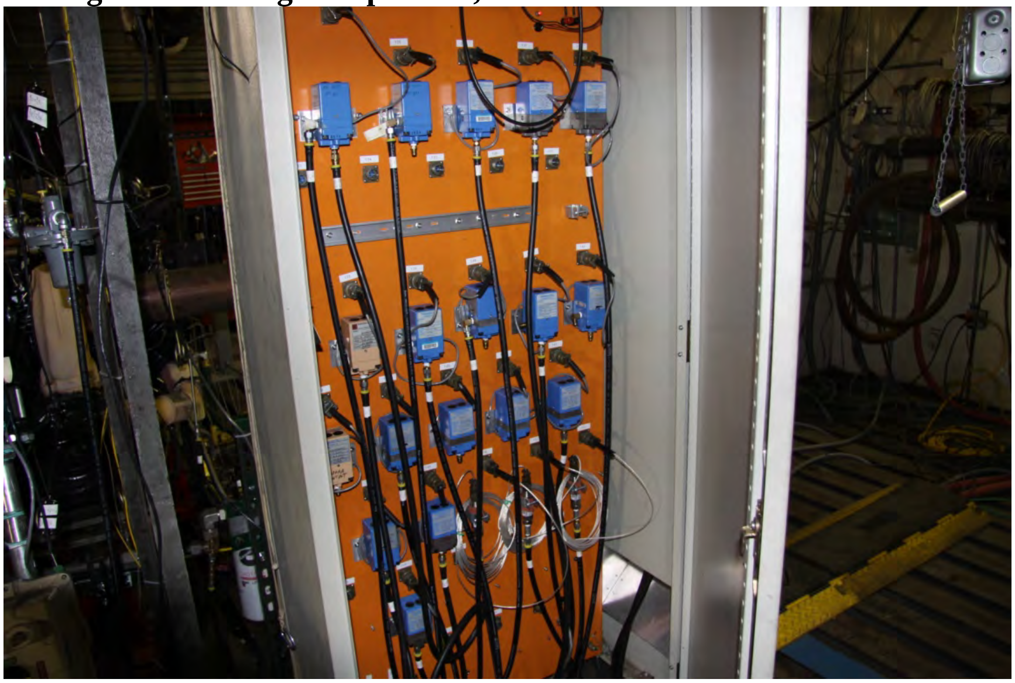

Table 3: Instrumentation List

Channel Name	ISO ABBREV	Quantity	Range	Units	Location Comments	PSL Number
Temperatures						
Air Cell Ambient Filter Inlet	T0	1		Deg F	J-Type Air Probe	
Air Before Compressor	T1	1		Deg F	J- Type Immersion Probe 1/8"	
Air After Compressor	T2	1		Deg F	J- Type Immersion Probe 1/8"	
Air CAC Out	T2'	1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Engine Supply		1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Engine Return		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant Engine In		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant Engine Out		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant CAC Out		1		Deg F	J- Type Immersion Probe 1/8"	
Oil Sump		1		Deg F	J- Type Immersion Probe 1/8"	
Oil Cooler In		1		Deg F	J- Type Immersion Probe 1/8"	
Oil Cooler Out		1		Deg F	J- Type Immersion Probe 1/8"	
Water Cooling Twr In		1		Deg F	J- Type Immersion Probe 1/8"	
Water Cooling Twr Out		1		Deg F	J- Type Immersion Probe 1/8"	
Water Dyno In		1		Deg F	J- Type Immersion Probe 1/8"	
Water Dyno Out		1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Return Post HX		1		Deg F	J-Type Immersion Probe 1/8"	
Fuel Beaker		1		Deg F	J-Type Immersion Probe 1/8"	
Transducer Rack		1		Deg F	J-Type Air Probe	

Exhaust Port 1L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 2L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 3L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 4L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 1R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 2R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 3R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 4R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Manifold LT	LT	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Manifold RT	RT	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Before Turbine L	LT3	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Before Turbine R	RT3	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Turbine Out (stack)	T4	1		Deg F	K-Type Immersion Probe 1/8"	
Pressures						
-						
Barometric Pressure	P0	1	800-1100	mBar	Control room	
Test Cell Depression		1	0-10	H2O	0-1 PSIG installed channel 128	
Air Compressor Inlet	P1	1	0-12	H2O	0-1 PSIG Installed channel 129	
Air After Compressor	P2	1	0-26	PSIG	0-30 PSIG installed channel 130	-
Air After CAC	P2'	1	0-22	PSIG	0-30 PSIG installed channel 144	-
Engine Coolant In			0-30	PSIG	0-30 PSIG installed channel 150	PSL 00623

Engine Coolant Out			0-30	PSIG	0-30 PSIG installed channel 151	PSL 00406
CAC Coolant Out			0-30	PSIG	0-30 PSIG installed channel 152	PSL 00622
Tower Water Pressure			0-100	PSIG	0-100 PSIG installed channel 132	
						-
Exhaust Turbine Inlet Left	P3	1	0-17	PSIG	0-30 PSIG installed channel 131	
Exhaust Turbine Inlet Right	P3	1	0-17	PSIG	0-30 PSIG installed channel 149	
Exhaust Turbine Out (stack)	P4	1	0-16	H2O	0-1 PSIG installed channel 138	
Fuel Supply		1	0-1	PSIG	Vacuum (0-15 PSIG installed channel)	
Fuel Return		1	0-1.23	PSIG	0-3 PSIG installed channel 141	
Rail Pressure		1	0-140	PSIG	0-300 PSIG installed channel 147	
Oil Pressure @ Idle	min	1	10	PSIG		
Oil Pressure @ 2900 RPM (Range)			40-60	PSIG	0-100 PSIG installed channel 154	
Oil Gallery Pressure		1	0-75	PSIG		
Crankcase Pressure		1	0-2	H2O	0-1 PSIG installed channel 139	
Dyno Water		1	100	PSIG	0-300 PSIG installed channel 148	
Flow						
-						

Crankcase Blowby		1	0-4	CFM	J-Tec with oil separator	PSL 00668
Fuel Consumption (rated)		1	201-207	LBS	Mass Weigh System	PSL 00489
Oil Cooler Flow (rated)		1	40	GPM	Oil Flow Meter with RTD reference	PSL 00450
Water Cooling Twr Flow (rated)		1	15	GPM	Water Flow meter (mag flow)	PSL 00250
					AXF040C 1.5"	
Airflow (rated)		1	1440	CFM	6" Vortex	PSL 00660
Misc						
Speed Dynamometer		1	0-5000	Rpm	From Dyne Systems	
Torque Dynamometer		1	0-5000	LB-FT	From Dyne Systems	
Throttle Position		1	0-100	%	From Dyne Systems	
Realative Humidity		1	0-100	%		
Realative Humidity Dry Bulb Temp		1	0-300	Deg F		
24VDC Battery Maintainer		1	0-15A	N/A	Battery charger in cell	
Smoke		1	0 to 10	FSN	Smoke Meter In cell One Exhaust Stack	PSL 00361
O2 Sensor (rated)			29.2	#Air/ #Fuel		PSL 00695

4 RESULTS

The Cummins 903 engine performed well during the modified NATO test. The engine made rated crankshaft horsepower numbers from 590 BHP (Brake Horsepower) at zero hours to 595 BHP at 400 hours during the JP-8, 77F air and 86F fuel performance runs. The engine lost about 5 percent of power during the elevated performance runs, 561 BHP at zero hour and 567 BHP at 400 hour. This power loss is expected when the ambient air and fuel increase from 77 deg F to 120 deg F and 86 deg F to 175 deg F respectively. This is proven by the volumetric energy density of the fuel, which at 86 deg F the density of the JP-8 fuel was measured to be 6.6496 lbm/gal and at 175 deg F the fuel density changed slightly and was measured to be 6.346 lbm/gal. If both densities are multiplied to the heating value of the JP-8 fuel, which are around 18,745 Btu/lb and the percent difference is taken from their products the results come close to 5 percent. Figures 9 through 12 show the performance runs for the standard and elevated temperature tests. The oil test data was also compared to data from engine number two from a previous Cummins 903 alternative fuels test run on JP-8 fuel and 15W40 oil under the same conditions.

Figure 9: 0hr Engine Power Curve, JP-8, 77F Air, 86F Fuel

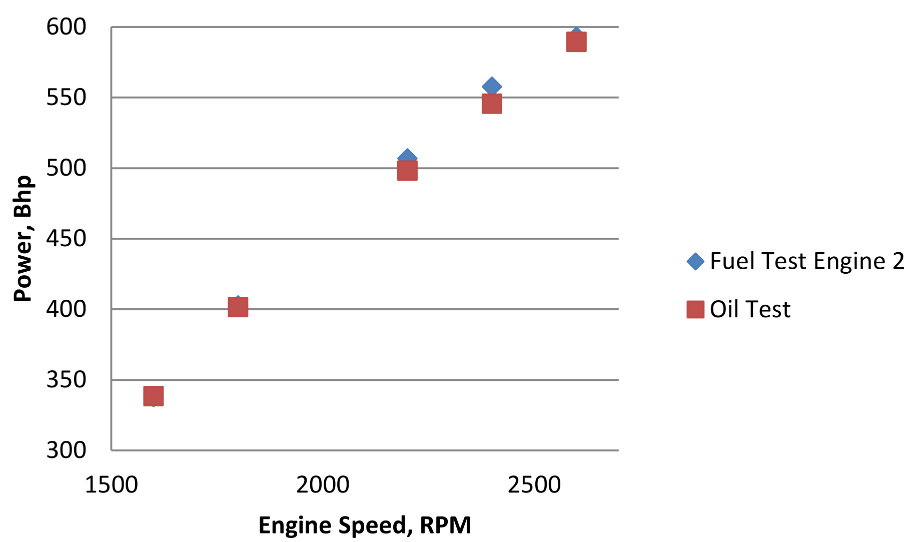

Figure 10: 0hr Engine Power Curve, 120F Air, 175F Fuel

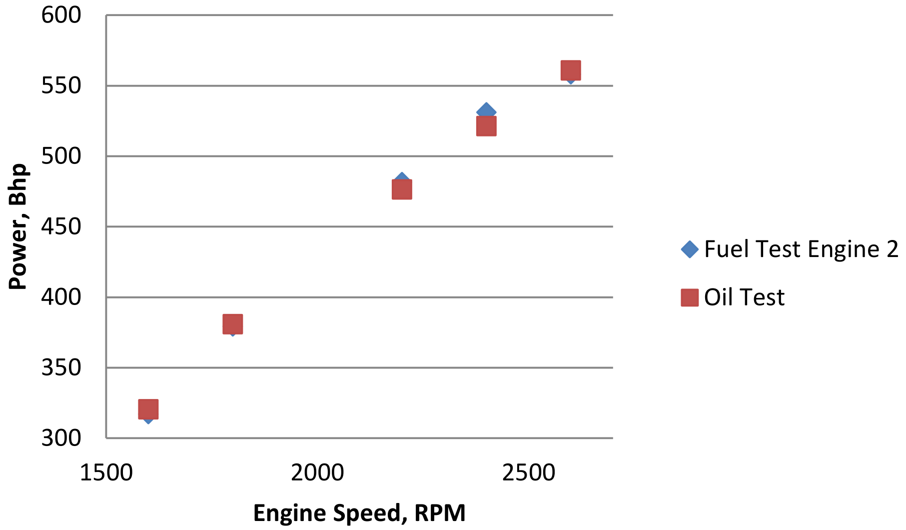

Figure 11: 400hr Engine Power Curve, JP-8, 77F Air, 86F Fuel

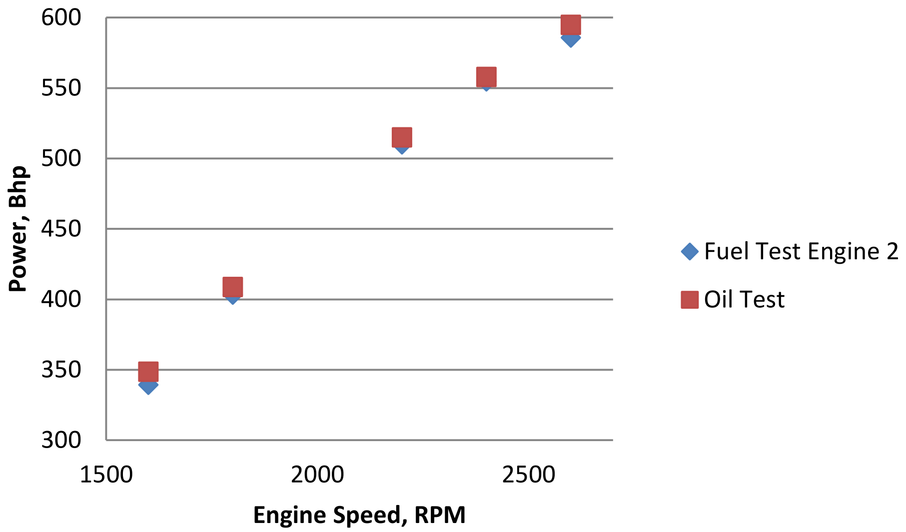

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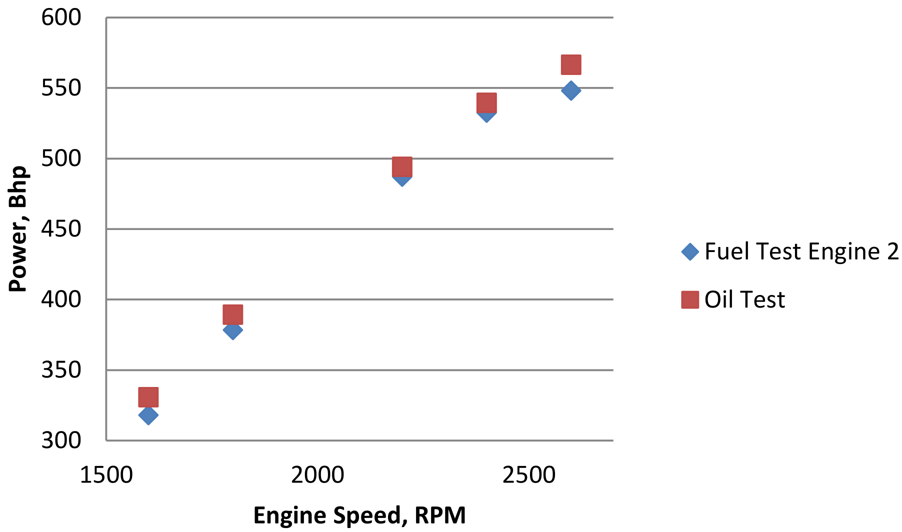
Figure 12: 400hr Engine Power Curve, JP-8, 120F Air, 175F Fuel



The difference in performance if any from 0 to 400hr's is relatively small between the two engines shown in Figures 9 through 12. Some of the performance difference can be attributed to the tolerances the engines were set to when they were rebuilt, and the different oils run in both engines.

Other than the power the engines efficiencies did not have much of a difference. The brake specific fuel consumption or BSFC, equation 1,

Equation 1: BSFC Calculation

$$BSFC = \frac{Fuel\ Consumption\ Flow\ rate}{Engine\ Brake\ Horse\ Power}$$

of both engines is the indicator that is used to measure the engines ability to convert fuel energy into useful mechanical energy. Figures 13 through 16 show the BSFC data for both the oil and fuel test engines.

Figure 13: 0hr Engine Brake Specific Fuel Consumption, JP-8, 77F Air, 86F Fuel

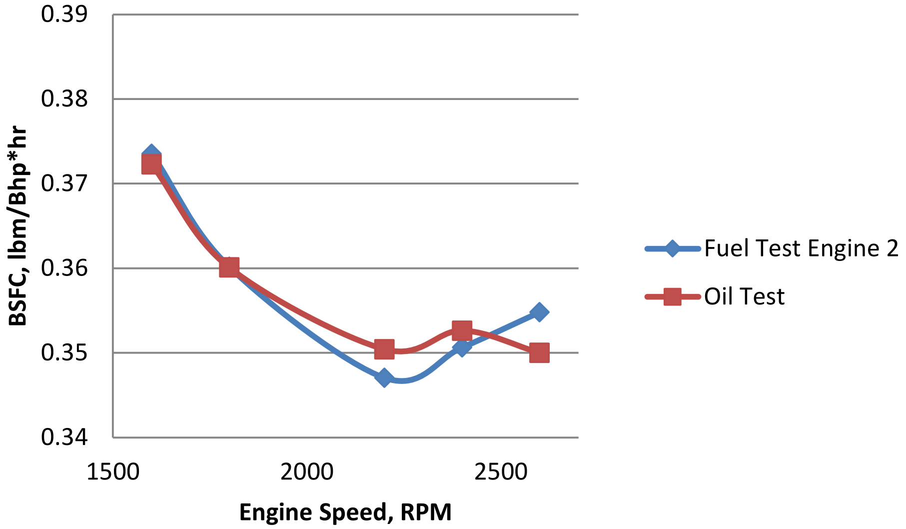


Figure 14: 0hr Engine Brake Specific Fuel Consumption, JP-8, 120F Air, 175F Fuel

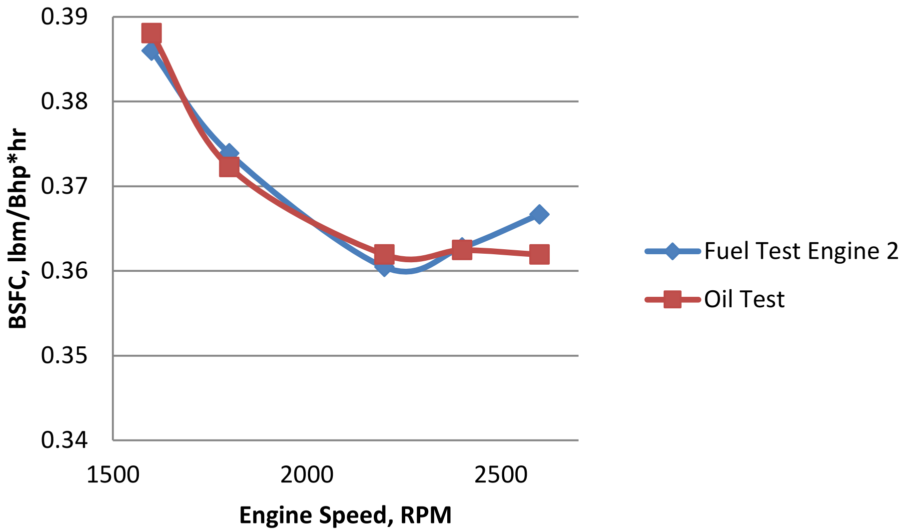


Figure 15: 400hr Engine Brake Specific Fuel Consumption, JP-8, 77F Air, 86F Fuel

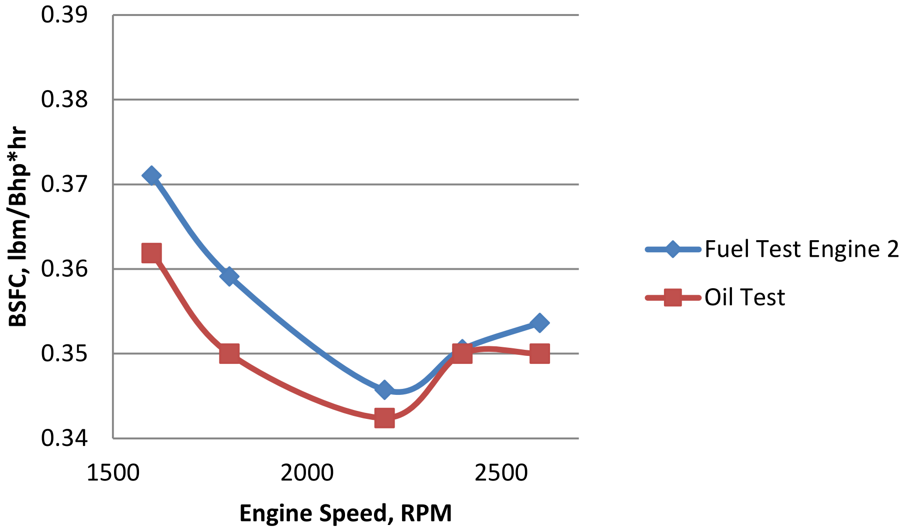
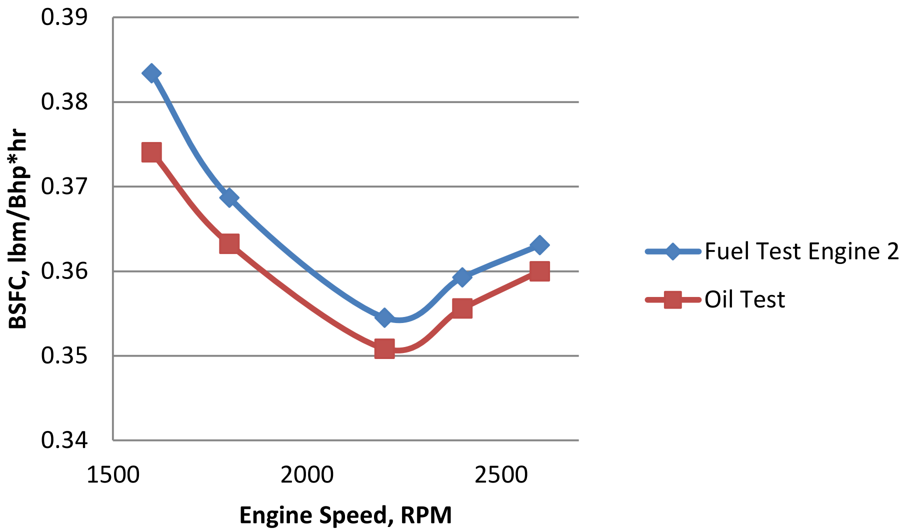


Figure 16: 400hr Engine Brake Specific Fuel Consumption, JP-8, 120F Air, 175F Fuel



Both engines showed a minimal difference in BSFC, the difference could be due to the difference in mechanical tolerances between both engines, which may be related to how the engines were rebuilt. Per customer data sheet provided by Cummins each engine coming of the assembly line has a tolerance of +/- 5% at rated power and peak torque. In addition, the fuel flow data toward the end of the oil testing was also influenced by a bad fuel cutoff valve, and further amplified by a failing fuel scale. These problems were remedied but the fuel cutoff and instrumentation even though new, may have influenced the outcome of the 400 hr data difference in engine efficiency between both engines.

The BSFC percent differences at 0 and 400 hours between both engines at 77 and 120 deg F ambient temperatures are as follows with respect to figures 13 through 16.

Table 4: BSFC Percent Difference Between Oil and Fuel Tests

Engine Speed, RPM	2600	2400	2200	1800	1600
77 deg F, 0hr, Fig 13	1.37%	0.57%	0.96%	0.02%	0.34%
77 deg F, 400hr, Fig 14	1.04%	0.16%	0.97%	2.61%	2.53%
120 deg F, 0hr, Fig 15	1.31%	0.09%	0.41%	0.43%	0.53%
120 deg F, 400hr, Fig 16	0.85%	1.03%	1.04%	1.51%	2.49%

The differences in engine efficiency are within the accuracy of the tests instrumentation uncertainty. Equation 2 was used to calculate the uncertainty data presented in Table 5, which shows the calculated total instrument uncertainty for each speed during the 0 and 400 hr performance tests at 77 and 120 deg F air, and 86 and 175 deg F fuel respectively. Uncertainty calculated in accordance with equation 2 assumes all errors adversely affect accuracy and therefore represents a worst case scenario.

Equation 2: BSFC Uncertainty

$$\pm BSFC\ Percent\ Uncertainty = \left\{\left(2 * \frac{dm}{m}\right) + \left(2 * \frac{dt}{t}\right) + \left(\frac{dL}{L}\right) + \left(\frac{dF}{F}\right) + \left(\frac{dN}{N}\right)\right\} \times 100$$

m – Fuel mass, (lb)
dm – Mass measurement uncertainty (+/- .0125 lb, based on .05% of 25 lb load cell)
t – Measured time between fuel mass readings (every 60 sec)
dt – Time measurement uncertainty, (.05 sec)
L – Load arm measured length, (21 in)
dL – Load arm length measurement uncertainty (.001 in)
F – Load cell measured force
dF – Load cell measurement uncertainty, (+/- 12 lb, based on .4% of 3000 lb load cell)
N – Measured dynamometer rotational speed, (RPM)
dN – Rotational speed measurement uncertainty (+/- 10)

Table 5: Oil Test Calculated Instrument Uncertainty

Engine Speed, RPM	2600	2400	2200	1800	1600
77 deg F, 0hr, Fig 13	3.2%	3.2%	3.3%	3.6%	3.8%
77 deg F, 400hr, Fig 14	3.2%	3.2%	3.2%	3.5%	3.7%
120 deg F, 0hr, Fig 15	3.3%	3.3%	3.4%	3.7%	3.9%
120 deg F, 400hr, Fig 16	3.3%	3.2%	3.3%	3.6%	3.8%

The blow-by engine data over the course of the 400 hour endurance run showed the engines blow-by to have been within the Cummins .25 - .5% of airflow limits for a properly functioning engine. Blow-by data is an indirect way of measuring engine wear within the engines cylinders and piston rings. Blow-by is defined as the gas that flows from the combustion chamber past the piston rings and into the crankcase, John B. Heywood (1988, p. 363). Figure 17 displays data relating to the full power portion, Sub-cycle 2, of the endurance test. The data shows a small increasing trend throughout the endurance test. Figures 18 and 19 show the data from a Cummins 903 alternative fuels test run on JP-8 and a 50/50 blend of JP-8 and FT-SPK fuel at 120 deg F air and 175 deg F fuel; the data shows that the blow-by was also small at rated power and fell within Cummins blow-by specifications. The data presented by the alternative fuels test engine run on JP-8 and 15W40, Figure 18, shows the engine to have lower blow-by than the engine run on JP-8 and low viscosity oil, Figure 17. This data when compared to a 3rd engine run on the 50/50 blend of JP-8 and FT-SPK and 15W40 oil shows to have a minimal, this data is a good indication in the variability between engines.

Figure 17: Engine Blow-by, JP-8, Low Viscosity Oil, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2

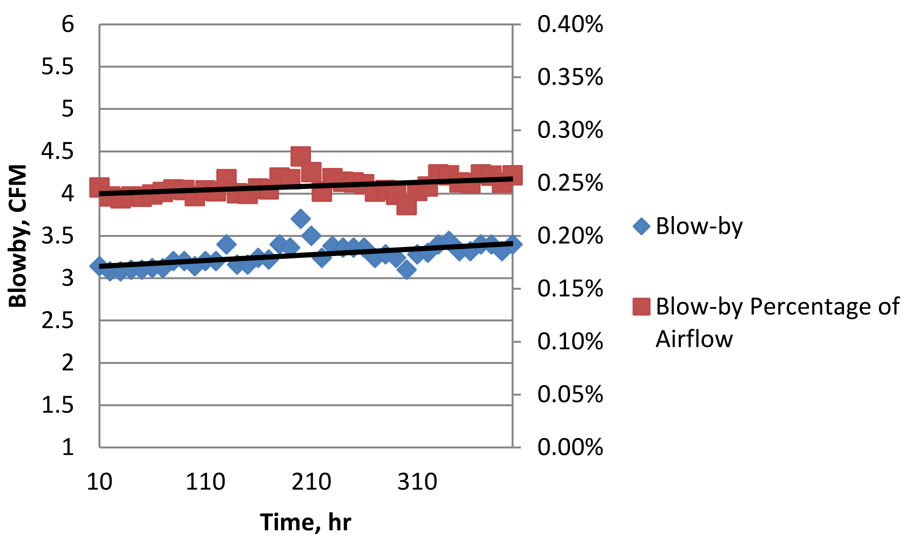


Figure 18: Alternative Fuel Test Blow-by, JP-8, 15W40, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2

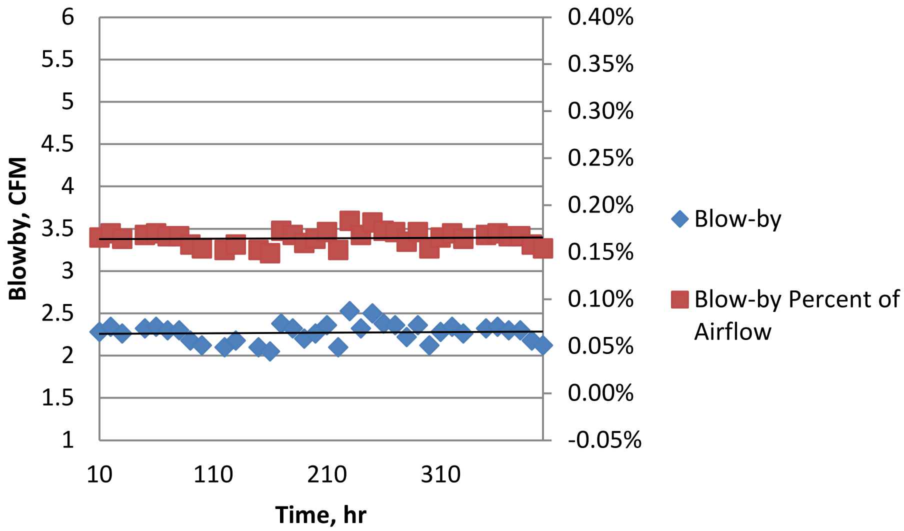
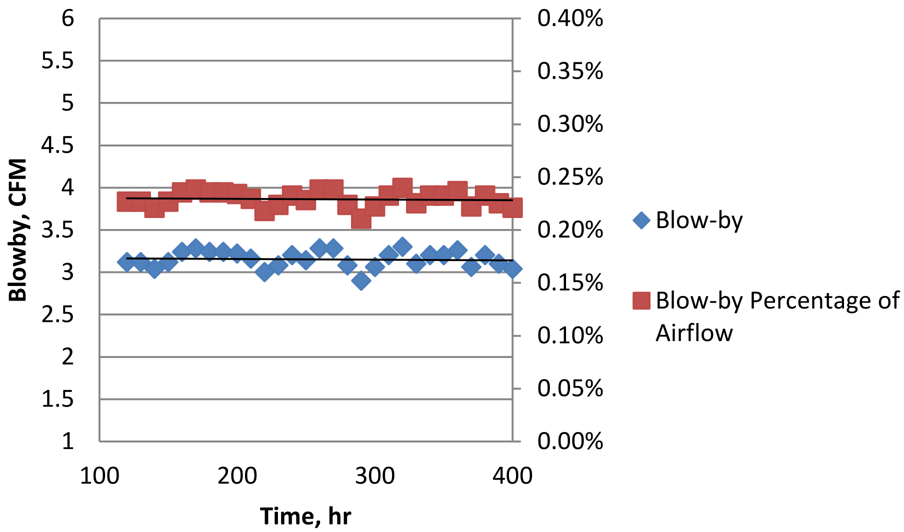


Figure 19: Alternative Fuel Test Blow-by, 50/50 JP-8/FT-SPK, 15W40, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2



The low viscosity oil test also showed some unusual trends during parts of the 400 hr endurance test. The engines oil pressure and flow rate fluctuated during parts of the test; and tracked as the oil pressure increased the oil flow decreased, as the oil pressure decreased the oil flow increased. Figures 20 through 23 showed these events happening at rated power (Sub-cycle 2) and peak torque (sub-cycle 9).

Figure 20: Oil Test Oil Pressure, JP-8, Low Viscosity Oil, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2

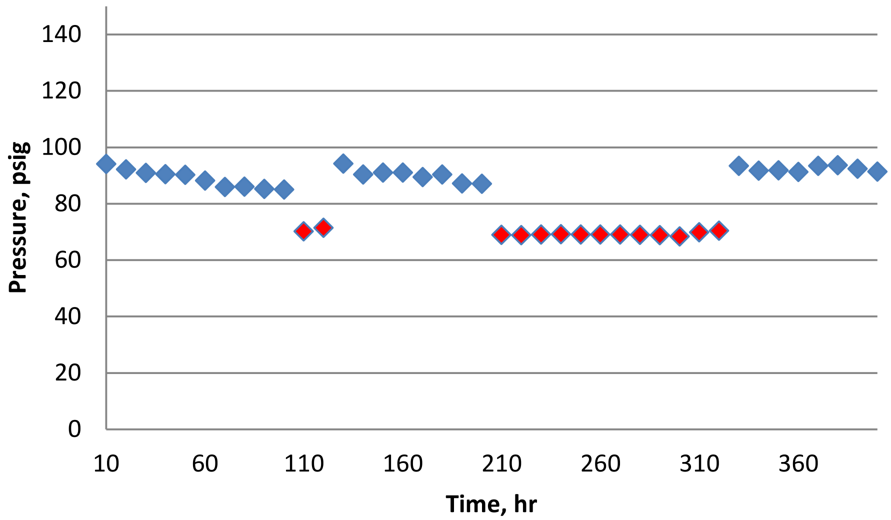


Figure 21: Oil Test Oil Flow, JP-8, Low Viscosity Oil, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2

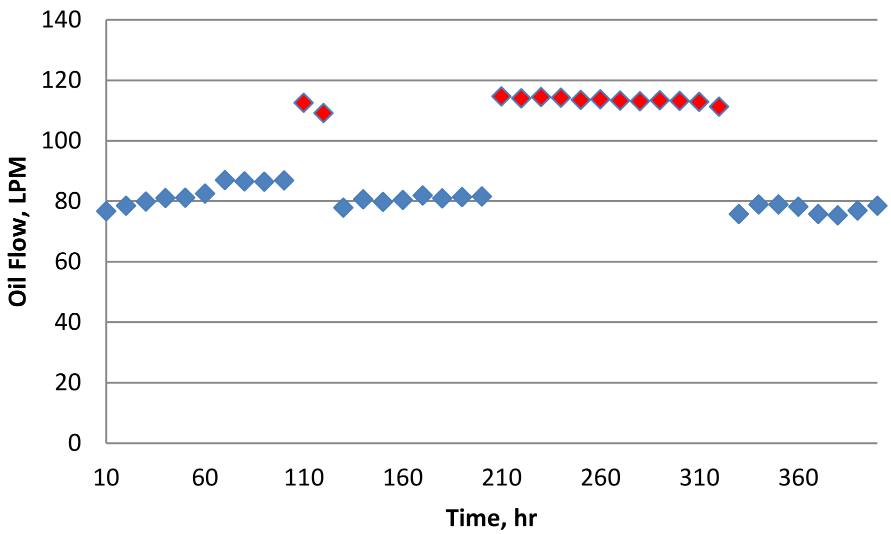


Figure 22: Oil Test Oil Pressure, JP-8, Low Viscosity Oil, 120F Air, 175F Fuel, 400hr, Peak Torque Sub-cycle 9

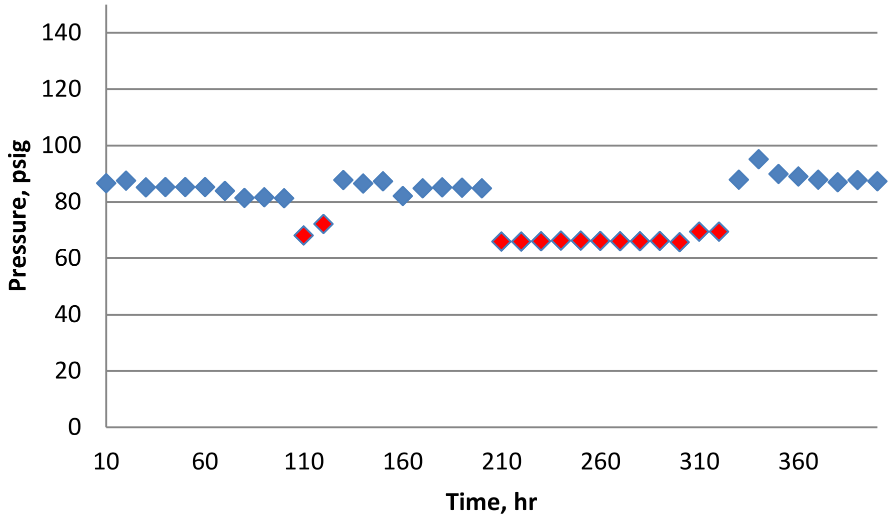
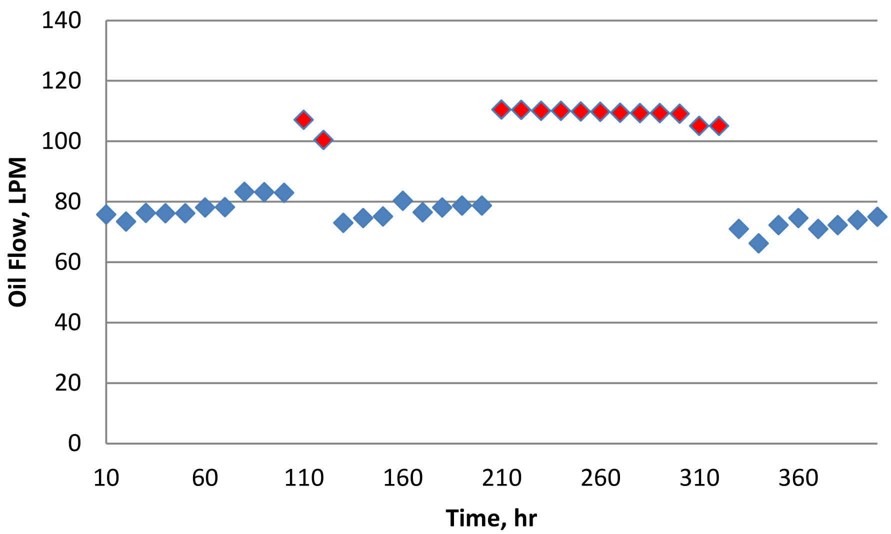


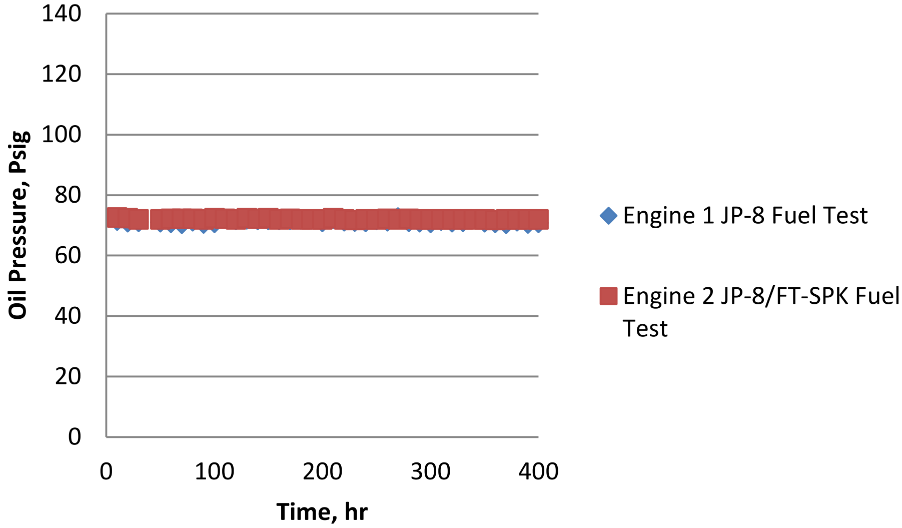
Figure 23: Oil Test Oil Flow, JP-8, Low Viscosity Oil, 120F Air, 175F Fuel, 400hr, Peak Torque Sub-cycle 9



The data in Figures 16 through 19 are unable to be explained without examining the engines internal parts. Debris may have caused an obstruction up stream of the flow, which could be to blame for the jump in pressure, and flow during the test. All test equipment, pressure transducers and flow meters, were verified to be in working order. The external oil lines were removed and inspected, but had no debris present to impede the flow across the external section of the oil circuit. Further engine hardware analysis will be done at Southwest Research.

Engine oil pressure data in Figure 20 pulled from the alternative fuel tests showed the pressure to hover around 72 psig both engines ran on 15W-40 oil; lower than oil test engine by 10 psig. Both engines did not experience the same pressure fluctuations as the engine ran on the low viscosity oil.

Figure 24: Alternative Fuel Test Oil Pressure, 15W40, 120F Air, 175F Fuel, 400hr, Full Power Sub-cycle 2



5 Conclusion

In conclusion, the data showed the engine to perform well while operating with the SCPL during the 400-hour endurance test under elevated temperature conditions. The SCPL engine had small immeasurable differences in performance when compared to the alternative fuels tests engines operated using standard military 15W-40. The SCPL engine also had normal blow-by readings, which is an indicator piston ring wear, throughout the 400-hour endurance test when compared to the two alternative fuel test engines that were tested under the same conditions. Further, engine wear inspections were done on all moving parts by Southwest Research in order to conclude the overall performance of the SCPL. The results of the engine inspection can be found in the Teardown and Inspection of the Cummins VTZ-903 – Evaluated Using The Single Common Powertrain Lubricant (SCPL) report written by Southwest Research Institute (SwRI).

6 ACKNOWLEDGEMENTS

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Dan Fawcett – Instrument Technician - TARDEC

Cummins 903 Engineering – Cummins

Dr. Pete Schihl – Senior Technical Expert for GVPM - TARDEC

APPENDIX A Test Plan

Test Plan

V903 Engine Modified NATO Endurance Oil Test

By

Test Engineers

Lead: John Hubble Jr

Eric Blash

Michael Claus

Version 3

1.0 BACKGROUND

The U.S. Army TARDEC Fuels and Lubricants Technology Team (FLTT) are seeking to develop an all-season (arctic-to-desert), fuel efficient, multi-functional power train fluid with extended drain capabilities. This program, known as the Single Common Power train Lubricant (SCPL) program, will leverage state-of-the-art base oil and additive technologies to significantly improve upon current military lubricants and act as an enabler for future power train technologies. The first phase of this program demonstrated the technical and economic feasibility of the SCPL concept. In the second and current phase, lessons learned from the technical feasibility will be used to guide the development of candidate SCPLs. Candidate SCPLs will be evaluated in military engines under conditions of elevated temperature in a laboratory environment. The third and final phase will demonstrate SCPLs candidates in an operational environment during field-testing throughout the CONUS.

2.0 OBJECTIVE

The objective of this test is to assess the impacts of a candidate SCPL on the performance and wear characteristics of a Cummins V903 600 hp diesel engine tested to a modified NATO protocol. Modifications include using JP-8 as the test fuel as well as running the engine under Desert Operating Conditions (DOC). Additionally, engine oil degradation will be assessed throughout the duration of the test to determine if extended oil change intervals can be achieved.

1. Engine performance will be assessed with full load performance runs at 100 hour intervals. Initial and final full load performance runs will be conducted using JP-8 as well as DF-2 at standard NATO conditions and at DOC.
2. Engine wear will be assessed through a post test inspection of critical engine components.
3. Engine oil degradation will be assessed with property test samplings at predetermined and, if necessary, intermediate intervals.

3.0 TEST SET-UP

1. Prepare the engine for performance and endurance testing.
    a. Dynamometer 700 horse power (absorption 1000-4000RPM), Mid-West 1521

   b. Coolant heat exchanger (water tower)
   c. Fuel supply heat exchanger electric heater
   d. Fuel return heat exchanger tube and shell
   e. Fill cooling system with a 50/50 blend of ethylene glycol and distilled water.
   f. Fill oil sump with candidate SCPL provide by TARDEC Fuels and Lubricants team.
2. Install and calibrate all instrumentation (See Table 1, Appendix A).
3. Conduct Engine Run In.
4. Conduct engine and instrumentation inspection before test (during Run In and 1st Performance test).
5. The following parameters are to be measured (or calculated) and recorded using standard laboratory instrumentation procedures.
   a. Engine Crankshaft Speed (RPM)
   b. Engine Output Torque (LB-FT)
   c. Engine Output Power (BHP)
   d. Ambient Air Temperature (deg F)
   e. Atmospheric Pressure (psi)
   f. Atmospheric Relative Humidity (%)
   g. Induction Air Temperature (deg F)
   h. Inlet Air Depression (in H20)
   i. Exhaust Backpressure (in H20)
   j. Exhaust Temperature Before Turbine (deg F)
   k. Exhaust Temperature After Turbine (deg F)
   l. Air Temperature After Compressor (deg F)
   m. Oil Sump Temperature (deg F)
   n. Oil Gallery Temperature (deg F)
   o. Oil Pressure (psi)
   p. Fuel Supply Temperature (deg F)
   q. Fuel Consumption (LB/HR)
   r. Fuel Supply Restriction (psi)
   s. Fuel Return Restriction (psi)
   t. Fuel Rail Pressure (psi)
   u. Brake Specific Fuel Consumption (LB/HP-HR)
   v. Blow By Gas Flow (CFM)
   w. Coolant Outlet Temp (deg F)
   x. Coolant Inlet Temp (deg F)
   y. Exhaust Smoke Bosch (smoke number)
   z. Volumetric Air Flow
   aa. Air Fuel ratio measurement
   bb. Heat Rejection
6. The following shut down limits shall be established.
   a. Maximum engine coolant out temperature of 230°F
   b. Maximum coolant pressure of 15 psi
   c. Maximum restriction at fuel pump inlet of 4.0 in-Hg

d. Maximum fuel return line restriction of 6.5 in-Hg
e. Engine oil temperature of 280°F measured at sump.
f. Minimum oil pressure of 10 psi.
g. Maximum oil pressure 40-60 psi
h. Maximum ail inlet restriction of 10 +/-2 in-H_2O
i. Maximum exhaust back pressure of 16 +/-2 in-H_2O

4.0 ENGINE RUN-IN

1. Engine run-in shall be performed at standard NATO condition outlined in Table 5.3, with DF-2 fuel.
2. Engine run-in shall be performed with the candidate SCPL provided by TARDEC Fuels and Lubricants team.
3. Table 4.1 outlines the run-in procedure provided by Cummins. The run-in procedure, resulting test data, warm up/cool down procedure and engine operating limits are being supplied to TARDEC by Cummins in order to start performance testing.

Table 4.1. Engine Run-In Procedure

Time (min)	Torque (ft-lbf)	Speed (RPM)
2	260	1200
2	590	1600
5	750	2100
5	875	2400
8	1200	2600

4. If you are using the thermostats that are supplied with the engine, be sure to install a bypass line from the stat housing to the coolant pump suction.
5. The bypass line is not needed if you remove the t-stats. If you remove the stats:
   a. Be sure to plug the bypass port on the stat housing.
   b. Be sure to limit coolant outlet temperature to around 200F.
6. Start the break-in after the engine has idled at 800 rpm and no load until the coolant outlet temp reaches 150F.
7. Use the fuel and oil filtration supplied.
8. Monitor the blow-by as follows:

a. Blow by should be between .25 and .5% of airflow for a good engine (3.6CFM and 7.2CFM of rated airflow 1440CFM)
b. Worn engine 1.5% of airflow (21.6CFM of rated airflow 1440CFM)

9. Set the inlet restriction to the turbocharger compressor at no more than 10 +/-2 in-H2O when at full load. Lock it in that position for the rest of the test.
10. Set the outlet restriction from the turbocharger turbine at no more than 3 in Hg when at full load. Lock it in that position for the rest of the test.

5.0 TEST PROCEDURES AND GUIDELINES

5.1 PERFOMANCE TESTING

All performance testing shall be performed at the set points outlined in Table 5.1. For each setting, the engine should be run for a sufficient amount of time to allow the operating parameters to stabilize. Part load data is to be recorded at the same pre-selected speeds as was used for the full load test. During this test, the smoke emissions as measured on the BOSCH Scale (or equivalent) shall not exceed 4.5 (Diesel engines only).

Table 5.1. Performance Testing Parameters

Engine Speeds (RPM)	1600, 1800, 2200, 2400*, 2600**
Loads	Full, 85%, 70%, 50%, 25%

* Peak torque (~1240 ft-lb on DF-2)

** Rated power (~600 HP on DF-2)

<u>Note: Part Load test points (85%, 70%, 50%, and 25%) will be calculated from full load performance run.</u>

5.2 ENDURANCE TESTING

All endurance testing shall be performed in accordance with Table 5.2. The engine shall be subjected to a 400 hour endurance test modified from AEP-5. Data shall be recorded during the last five minutes of each sub-cycle excluding sub-cycle 5. If the engine and/or its subsystems exceeds established limit conditions and the sub-cycle must be aborted, the sub-cycle may be restarted from the beginning, pending an Engineer’s decision. The engine may be turned off upon completion of any sub-cycle and may later be restarted into the next sub-cycle without penalty; following the manufacturer's defined warm-up/cool down procedure.

Table 5.2. Endurance Testing Parameters

Program of 10 Hour Cycle				
sub-cycle	% Rated Speed	RPM	% Load	Duration in hrs
1	Idle (1)	800 +/-25	0	0.5
2	100	2600	100 (5)	2
3	Governed speed (2)	2600	0	0.5
4	75	1950	100 (5)	1
5	Idle (1)_(3)_100		0(4min)__100(6min)	2
6	60	1560	100	0.5
7	Idle (1)	800 +/-25	0	0.5
8	Governed speed (4)	2600	70 (6)	0.5
9	Max Torque Speed	2000	100 (5)	2
10	60	1560	50 (6)	0.5
Total				10

(1) Deviation from regulated coolant and fuel temperature is permitted in this sub-cycle
(2) The engine speed shall be obtained with the engine at full throttle and with minimum load
(3) The control movement from IDLE to 100% rated speed/load shall occur within 3 seconds
(4) The engine speed shall be the steady speed of the engine at full throttle and 70% of the rated load
(5) One-hundred percent load shall be governed by full throttle
(6) Part loads shall be determined based on the initial performance test

5.3 TEST CONDITIONS

Operating conditions are defined and outlined in Table 5.3.

Table 5.3. Test Operating Conditions

Condition	**Standard**	**Desert (DOC)**
Inlet Air Temperature (°F)	77	120
Fuel Supply Temperature (°F)	86	175
Engine Coolant Out Temperature (°F)	205+/-5	218+/-5
Intake Restriction (in-H_2O)	10+/-2	10+/-2
Exhaust Restriction (in-H_2O)	16+/-2	16+/-2

5.4 TEST PROCEDURE

The following sequence outlines the test procedures, in chronological order, that shall be followed throughout the duration of the test. Data shall be recorded at the end of every 10 hour sub cycle. Daily test reports regarding incidents and data measurements shall be provided for engineering analysis unless otherwise indicated.

1. JP-8 Fuel characterization. Samples will be taken from the engines fuel delivery line after the fuel filter. Fuels will be characterized per MILDTL-83133F.
2. Initial performance testing with JP-8 Fuel at Standard conditions and DOC in accordance with Table 5.1.
3. Part Load Testing
4. 50 hour oil sample
5. 100 Hr Modified NATO endurance testing at DOC with JP-8 Fuel in accordance with table 5.2. Note, additional oil extraction and sampling may occur during this portion of the test with possible decisions to perform oil and filter change. Collect a 250 mL oil sample at every 100 hr maintenance interval.
6. Performance testing with JP-8 Fuel at Standard conditions and DOC in accordance with Table 5.1.
7. 100hr Oil and Fuel extraction for characterization. Oil shall be purged from the engine only when fully warmed and well mixed to ensure a

homogeneous representative sample. Based on the results of oil testing, a decision will be made to either continue testing with no oil/filter change or to change the oil and filter prior to proceeding.

8. 150 hour oil sample
9. 200 Hr Modified NATO endurance testing at DOC with JP-8 Fuel in accordance with table 5.2. Note, additional oil extraction and sampling may occur during this portion of the test with possible decisions to perform oil and filter change. Collect a 250 mL oil sample at every 100 hr maintenance interval.
10. Performance testing with JP-8 Fuel at Standard conditions and DOC in accordance with Table 5.1.
11. Oil and Fuel extraction for characterization. Based on the results of oil testing, a decision will be made to either continue testing with no oil/filter change or to change the oil and filter prior to proceeding.
12. 250 hour oil sample
13. 300 Hr Modified NATO endurance testing at DOC with JP-8 Fuel in accordance with table 5.2. Note, additional oil extraction and sampling may occur during this portion of the test with possible decisions to perform oil and filter change.
14. Performance testing with JP-8 Fuel at Standard conditions and DOC in accordance with Table 5.1.
15. Oil and Fuel extraction for characterization. Based on the results of oil testing, a decision will be made to either continue testing with no oil/filter change or to change the oil and filter prior to proceeding.
16. 350 hour oil sample
17. 400 Hr Modified NATO endurance testing at DOC with JP-8 Fuel in accordance with table 5.2. Note, additional oil extraction and sampling may occur during this portion of the test with possible decisions to perform oil and filter change.
18. Final performance testing with JP-8 Fuel at Standard conditions and DOC in accordance with Table 5.1.
19. Final Part Load Testing
20. Oil extraction for characterization.
21. JP-8 Fuel characterization. Samples will be taken from the engines fuel delivery line after the fuel filter. Fuels will be characterized per MILDTL-83133F.
22. Final Report will be written after all testing and inspections have been concluded.
23. Engine will be drained of all fluids, packaged and shipped to the Army F&L (fuels and lubes) lab at SwRI (Southwest Research Institute)

5.5 ENDURANCE TEST PASS/FAIL CRITERIA

A failure is defined as either major or minor.

1. A major failure occurs when any part or component of the engine assembly leads to a final stoppage of the engine or brings about a loss of power which cannot be rectified to give at least 95% of the initial measured peak power and/or peak torque within the scope of normal maintenance. Any major failure will lead to termination of the test and any retest must start at hour zero.

2. A minor failure occurs when there is more than a 5% loss in measured peak power and/or peak torque during the full-load performance check that is remedied within the scope of normal maintenance. If 95% of the measured peak power and/or peak torque cannot be obtained through normal maintenance, then the test will be reassessed as a major failure.

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Appendix A

Channel Name	ISO ABBREV	Quantity	Range	Units	Location Comments	PSL Number
Temperatures						
Air Cell Ambient Filter Inlet	T0	1		Deg F	J-Type Air Probe	
Air Before Compressor	T1	1		Deg F	J- Type Immersion Probe 1/8"	
Air After Compressor	T2	1		Deg F	J- Type Immersion Probe 1/8"	
Air CAC Out	T2'	1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Engine Supply		1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Engine Return		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant Engine In		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant Engine Out		1		Deg F	J- Type Immersion Probe 1/8"	
Coolant CAC Out		1		Deg F	J- Type Immersion Probe 1/8"	
Oil Sump		1		Deg F	J- Type Immersion Probe 1/8"	

Oil Cooler In		1		Deg F	J- Type Immersion Probe 1/8"	
Oil Cooler Out		1		Deg F	J- Type Immersion Probe 1/8"	
Water Cooling Twr In		1		Deg F	J- Type Immersion Probe 1/8"	
Water Cooling Twr Out		1		Deg F	J- Type Immersion Probe 1/8"	
Water Dyno In		1		Deg F	J- Type Immersion Probe 1/8"	
Water Dyno Out		1		Deg F	J- Type Immersion Probe 1/8"	
Fuel Return Post HX		1		Deg F	J-Type Immersion Probe 1/8"	
Fuel Beaker		1		Deg F	J-Type Immersion Probe 1/8"	
Transducer Rack		1		Deg F	J-Type Air Probe	
Exhaust Port 1L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 2L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 3L		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 4L		1		Deg F	K-Type Immersion Probe 1/8"	

Exhaust Port 1R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 2R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 3R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Port 4R		1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Manifold LT	LT	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Manifold RT	RT	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Before Turbine L	LT3	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Before Turbine R	RT3	1		Deg F	K-Type Immersion Probe 1/8"	
Exhaust Turbine Out (stack)	T4	1		Deg F	K-Type Immersion Probe 1/8"	
Pressures						
-						
Barometric Pressure	P0	1	800-1100	mBar	Control room	
Test Cell Depression		1	0-10	H2O	0-1 PSIG installed channel 128	
Air Compressor Inlet	P1	1	0-12	H2O	0-1 PSIG Installed channel 129	

Air After Compressor	P2	1	0-26	PSIG	0-30 PSIG installed channel 130	-
Air After CAC	P2'	1	0-22	PSIG	0-30 PSIG installed channel 144	-
Engine Coolant In			0-30	PSIG	0-30 PSIG installed channel 150	PSL 00623
Engine Coolant Out			0-30	PSIG	0-30 PSIG installed channel 151	PSL 00406
CAC Coolant Out			0-30	PSIG	0-30 PSIG installed channel 152	PSL 00622
						-
Exhaust Turbine Inlet Left	P3	1	0-17	PSIG	0-30 PSIG installed channel 131	

Exhaust Turbine Inlet Right	P3	1	0-17	PSIG	0-30 PSIG installed channel 149	
Exhaust Turbine Out (stack)	P4	1	0-16	H2O	0-1 PSIG installed channel 138	
Fuel Supply After Filter		1	0-2	PSIG	Vacuum (0-3 PSIG installed channel 143)	
Fuel Return		1	0-1.23	PSIG	0-3 PSIG installed channel 141	
Rail Pressure		1	0-140	PSIG	0-300 PSIG installed channel 147	
Oil Pressure @ Idle	min	1	10	PSIG		
Oil Pressure @ 2900 RPM (Range)			40-60	PSIG	0-100 PSIG installed channel 154	
Oil Gallery Pressure		1	0-75	PSIG		
Crankcase Pressure		1	0-2	H2O	0-1 PSIG installed channel 139	

Dyno Water		1	100	PSIG	0-300 PSIG installed channel 148	
Flow						
-						
Crankcase Blow by		1	0-4	CFM	J-Tec with oil separator	PSL 00668
Fuel Consumption (rated)		1	201-207	LBS	Mass Weigh System	
Oil Cooler Flow (rated)		1	40	GPM	Oil Flow Meter with RTD reference	PSL 00450
Water Cooling Twr Flow (rated)		1	15	GPM	Water Flow meter (mag flow)	PSL 00250
					AXF040C 1.5"	

Airflow (rated)		1	1440	CFM	6" Vortex	PSL 00660
Misc						
Speed Dynamometer		1	0-5000	Rpm	From Dyne Systems	
Torque Dynamometer		1	0-5000	LB-FT	From Dyne Systems	
Throttle Position		1	0-100	%	From Dyne Systems	
Relative Humidity		1	0-100	%		
Relative Humidity Dry Bulb Temp		1	0-300	Deg F		
24VDC Battery Maintainer		1	0-15A	N/A	Battery charger in cell	
Smoke		1	0 to 10	FSN	Smoke Meter In cell One Exhaust Stack	PSL 00361

Test Map

	Start	Completion
Pull Clean Sample from 55 gallon Drum		

JP-8 Engine Run-In, 77F air, 86F fuel		
Change Oil/Oil Filter		

JP-8 Full Load NATO, 77F air, 86F fuel		
JP-8 Part Loads NATO, 77F air, 86F fuel		
JP-8 Full Load DOC, 120F air, 175F fuel		
JP-8 Part Loads DOC, 77F air, 175F fuel		
Change Oil/Oil Filter, Pull Sample		

DOC		
Complete 50 hr durability, Pull Oil Sample		
Complete 100 hr durability		
JP-8 full load NATO, 77F air, 86F fuel		
JP-8 full load DOC, 120F air, 175F fuel		
Change Oil/Oil Filter, Pull Sample		

DOC		
Complete 150 hr durability, Pull Oil Sample		
Complete 200 hr durability		
JP-8 full load NATO, 77F air, 86F fuel		

JP-8 full load DOC, 120F air, 175F fuel		
Change Oil/Oil Filter, Pull Sample		

DOC		
Complete 250 hr durability, Pull Oil Sample		
Complete 300 hr durability		
JP-8 full load NATO, 77F air, 86F fuel		
JP-8 full load DOC, 120F air, 175F fuel		
Change Oil/Oil Filter, Pull Sample		

DOC		
Complete 350 hr durability, Pull Oil Sample		
Complete 400 hr durability		
JP-8 Full Load NATO, 77F air, 86F fuel		
JP-8 Part Loads NATO, 77F air, 86F fuel		
JP-8 Full Load DOC, 120F air, 175F fuel		
JP-8 Part Loads DOC, 77F air, 175F fuel		
Pull Oil Sample		

903 oil and Fuel Sampling

Oil Samples			
Test Time hr	Date Pulled	Notes	Quantity
0			8 oz
50			8 oz
100			8 oz
150			8 oz
200			8 oz
250			8 oz
300			8 oz
350			8 oz
400			8 oz

Fuel Samples			
TestTime hr	Date Pulled	Fuel Type	Quantity
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon
		JP-8	1 gallon

Approval Signature Blocks

TARDEC:

Approver: ____________________ Date: _________________

Mike Reid, Team Lead,

Testing, Evaluation & Assessment Team

Fuels and Lubricants Team:

Approver: ____________________ Date: _________________

Allen Comfort

Fuels and Lubricants Team

APPENDIX B Test Data

The following test data was used to create Figures 10-12 in the Results Section.

Synthetic Oil Test Performance Data, 77 deg F air, 86 deg F fuel, JP-8 Fuel

		0hr JP-8					100hr JP-8					200hr JP-8					300hr JP-8					400hr JP-8				
Percent Load	%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ambient																										
Air T0	Deg F	78	78	78	78	77	77	77	77	77	77	78	78	78	78	78	78	78	78	77	78	78	78	78	78	78
Air P0	inHg	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	30	30	30	29	29	29	29	29	29	29
Performance																										
Speed	RPM	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600
Torque	ft-lbf	1193	1196	1192	1174	1113	1219	1232	1229	1184	1130	1226	1230	1235	1195	1149	1217	1234	1240	1201	1155	1204	1223	1231	1195	1146
Power	hp	590	546	498	402	339	602	562	514	405	344	606	561	517	409	349	602	563	519	411	351	595	558	515	409	349
BMEP	Psi	199	200	199	196	186	204	206	205	198	189	205	205	206	200	192	203	206	207	201	193	201	204	206	200	191
Fuel																										
BSFC	lbm/hp*hr	0.35	0.35	0.35	0.36	0.37	0.35	0.35	0.34	0.35	0.36	0.34	0.34	0.33	0.35	0.36	0.34	0.34	0.33	0.34	0.35	0.35	0.35	0.34	0.35	0.36
inj. Vol	mm³/cycle	181	183	183	184	180	184	186	181	181	179	182	184	181	180	179	181	180	179	177	177	183	185	184	182	181
Flow	lbm/hr	206	193	176	145	126	209	195	175	142	125	207	193	174	142	125	206	189	172	139	124	208	194	177	144	127
Temp	Deg F	88	87	87	87	87	86	85	86	87	87	93	93	94	95	95	82	82	83	85	85	81	85	86	86	87
Oil																										
Sump Temp	Deg F	252	249	247	245	241	251	250	248	245	244	251	249	247	244	243	250	248	246	244	243	254	252	249	243	242
Pressure	psig	73	71	70	63	56	73	72	70	64	56	73	71	69	62	55	73	72	69	63	55	102	101	98	90	86
Oil Flow	lpm	111	110	107	99	91	114	112	109	101	93	115	113	110	102	93	114	112	109	101	93	67	67	64	59	57
Engine Coolant																										
Temp In	Deg F	196	196	196	195	195	196	196	196	196	195	195	196	196	196	195	196	196	196	196	196	196	196	196	196	196
Temp Out	Deg F	206	206	206	206	206	206	206	206	206	206	206	207	207	206	206	206	206	206	206	206	207	207	207	207	207

Inlet Air																										
t1	Deg F	78	78	78	79	78	76	76	76	77	77	77	78	78	78	79	76	77	77	77	78	78	78	78	79	79
P0-P1	inH2O	-12	-9	-7	-4	-2	-14	-10	-8	-3	-2	-14	-10	-7	-3	-2	-14	-10	-7	-3	-2	-13	-10	-7	-3	-1
t2	Deg F	303	282	259	218	194	314	293	269	221	198	314	292	269	222	199	314	291	268	220	199	310	288	265	220	199
P2	PSIG	22	20	17	12	10	23	21	18	12	10	23	21	18	12	10	23	21	18	12	10	23	20	18	12	10
t2'	Deg F	77	92	90	82	77	81	83	60	68	70	66	77	58	64	70	51	49	42	45	55	80	78	70	74	75
P2-P2'	PSIG	0.29	0.30	0.28	0.24	0.17	-0.66	-0.53	-0.41	-0.24	-0.15	-0.68	-0.52	-0.46	-0.26	-0.20	-0.74	-0.56	-0.49	-0.29	-0.23	-0.34	-0.19	-0.16	-0.09	-0.09
Air Flow	CFM	1297	1138	974	682	541	1364	1204	1024	696	555	1372	1199	1024	698	558	1383	1197	1024	697	558	1343	1177	1009	691	552
Exhaust																										
t3	Deg F	1168	1187	1209	1308	1354	1149	1166	1188	1276	1328	1147	1163	1186	1272	1325	1143	1158	1181	1267	1322	1162	1180	1203	1290	1345
P3	PSIG	15	12	10	6	5	16	14	11	7	5	16	13	11	7	6	16	13	11	7	5	15	13	11	7	5
t4	Deg F	955	992	1032	1160	1205	926	961	1002	1124	1184	924	960	1000	1120	1181	921	956	997	1115	1179	936	980	1025	1138	1197
P4-P0	inH2O	16	13	11	6	5	18	15	12	6	5	18	15	12	6	5	18	15	12	6	5	17	15	12	6	5
Smoke	AVL	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.4	1.2	2.1	0.3	0.3	0.5	1.2	2.1	0.3	0.3	0.4	1.2	2.1	0.5	0.4	0.6	1.5	2.2
Blow-by	CFM	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	3	3

Synthetic Oil Test Performance Data, 120 deg F air, 175 deg F fuel, JP-8 Fuel

				0hr JP-8					100hr JP-8					200hr JP-8					300hr JP-8					400hr JP-8		
Percent Load	%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ambient																										
Air T0	Deg F	119	119	119	118	119	120	119	120	120	120	119	119	119	119	119	119	119	119	119	119	119	119	119	119	119
Air P0	inHg	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
Performance																										
Speed	RPM	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600	2600	2400	2200	1800	1600
Torque	ft-lbf	1135	1143	1139	1113	1053	1161	1184	1180	1140	1083	1174	1192	1181	1146	1098	1168	1187	1185	1144	1096	1147	1183	1182	1138	1087
Power	hp	561	521	476	381	320	574	540	493	390	329	580	544	494	392	334	577	542	496	392	333	567	540	494	389	331
BMEP	Psi	190	191	190	186	176	194	198	197	190	181	196	199	197	191	183	195	198	198	191	183	191	198	197	190	182
Fuel																										
BSFC	lbm/hp*hr	0.36	0.36	0.36	0.37	0.39	0.35	0.34	0.34	0.36	0.38	0.34	0.35	0.34	0.35	0.37	0.33	0.32	0.32	0.32	0.34	0.36	0.36	0.35	0.36	0.37
inj. Vol	mm^3/cycle	179	180	179	180	178	176	177	175	181	179	174	179	175	174	174	166	167	166	157	162	178	183	181	179	178
Flow	lbm/hr	203	189	172	142	125	201	185	169	142	125	198	187	168	137	122	189	175	159	124	113	203	192	174	141	124
Temp	Deg F	175	175	178	178	178	175	178	180	173	177	176	176	177	179	176	175	176	175	178	178	176	175	176	180	179
Oil																										
Sump Temp	Deg F	268	266	262	257	256	265	264	262	259	258	264	263	261	258	257	263	262	260	258	257	263	259	258	255	255
Pressure	psig	99	98	95	87	83	70	69	68	58	50	70	68	67	57	49	70	69	67	58	51	97	95	92	84	80
Oil Flow	lpm	70	69	67	63	61	114	112	109	98	90	115	114	111	99	90	114	112	110	99	90	74	73	71	68	66
Engine Coolant																										
Temp In	Deg F	207	207	207	206	206	208	208	208	208	207	208	208	208	208	208	208	208	208	208	207	209	209	209	209	208
Temp Out	Deg F	218	218	218	218	218	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	220	220	220	220	220

Inlet Air																										
t1	Deg F	120	119	120	119	120	121	120	121	121	121	119	119	120	120	120	121	121	120	121	120	119	120	120	120	120
P0-P1	inH2O	-10	-8	-6	-3	-1	-11	-9	-6	-3	-1	-11	-9	-6	-2	-1	-12	-9	-6	-2	-1	-11	-9	-6	-2	-1
t2	Deg F	340	319	298	257	234	354	334	311	266	243	351	332	308	263	242	357	335	311	265	243	344	325	303	260	239
P2	PSIG	19	17	15	11	8	20	18	16	11	9	20	19	16	11	9	20	18	16	11	9	19	18	16	11	9
t2'	Deg F	239	232	226	215	211	243	236	230	218	213	242	236	229	187	191	228	216	197	187	170	216	208	216	187	191
P2-P2'	PSIG	0.30	0.28	0.22	0.15	0.13	0.49	0.42	0.37	0.24	0.18	0.38	0.30	0.24	0.16	0.12	0.52	0.46	0.38	0.26	0.21	0	0	0	0	0
Air Flow	CFM	1272	1120	969	685	547	1329	1180	1016	706	567	1332	1179	1011	705	568	1349	1187	1021	709	570	1302	1151	995	696	559
Exhaust																										
t3	Deg F	1242	1259	1279	1367	1415	1226	1246	1266	1352	1404	1219	1241	1258	1344	1398	1226	1244	1262	1346	1401	1235	1258	1278	1359	1415
P3	PSIG	13	11	9	6	4	14	12	10	6	5	14	12	10	7	5	14	12	10	6	5	13	12	10	6	5
t4	Deg F	1030	1063	1101	1217	1271	1008	1043	1080	1196	1254	1001	1039	1074	1188	1248	1004	1041	1077	1188	1249	1020	1065	1101	1203	1261
P4-P0	inH2O	15	13	10	6	5	16	14	10	6	5	16	14	11	6	5	16	14	11	6	5	15	14	10	6	5
Smoke	AVL	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.7	1.6	2.4	0.4	0.5	0.7	1.7	2.4	0.4	0.6	0.8	1.7	2.4	1	1	1	2	3
Blow-by	CFM	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2

Appendix C Equations

Equation 1C (Torque)

$$\text{Torque (ft} - \text{lb)} = \text{Load Cell Force (lb)} \times \text{Load Arm Length(ft)}$$

Equation 2C (Engine Brake Power, Bhp)

$$\boldsymbol{BHP} = \frac{N * T}{5252}$$

Equation 3C (Mass Flow Rate, $\dot{m}$)

$$\dot{m} = \rho * \dot{V}$$

Equation 4C (Brake Specific Fuel Consumption, $BSFC$)

$$BSFC = \frac{\dot{m}}{Bhp}$$

Equation 5C (Break Mean Effective Pressure, *BMEP*)

$$BMEP = \frac{75.4 * n_r * T}{V_d}$$

Symbol Definition:

F – Load Cell Force, lbf
L - Load Arm Length, ft
N – Engine Speed, RPM
T – Engine Torque, ft-lb
ρ – Fluid Density, lbm/ft^3
$\dot{V}$ – Volumetric Flow Rate of Fluid
n_r – Number of cycles, 2 for a 4-stroke engine, 1 for a 2-stroke engine
V_d – Engine displaced volume, in^3